

1     "X-Ray Topographic System"

2

3     This invention relates to an X-ray topographic  
4     system for use in examining crystal structures, for  
5     example silicon single-crystal wafers or boules for  
6     use in the production of semiconductors.

7

8     Background to the Invention

9

10    It is known to examine, for example, silicon wafers  
11    by means of X-rays to detect flaws such as slip  
12    bands which are nucleated during the rapid thermal  
13    annealing process. Such examination has hitherto  
14    been carried out by means of a Lang camera making an  
15    exposure on film. Prior art processes have suffered  
16    from a number of disadvantages, including the large  
17    size of the camera system, limitations on the size  
18    of the wafer which can be examined, and long  
19    processing times (typically about one hour for an 8"  
20    or 200 mm wafer).

21

1 One object of the present invention is to provide an  
2 X-ray topographic system which is capable of  
3 examining large samples, typically up to 300 mm  
4 diameter, and carrying out examinations rapidly,  
5 typically 5 to 15 minutes.

6  
7 Summary of the Invention

8  
9 Accordingly, the present invention provides an X-ray  
10 topographic system comprising:

11 an X-ray generator for producing a beam of  
12 X-rays directed towards a sample location; and  
13 a detector positioned to receive X-rays  
14 deflected by a sample at the sample location, the  
15 detector comprising an electronic X-ray detector  
16 having an array of pixels corresponding to the beam  
17 area.

18  
19 The X-ray beam may have a relatively large  
20 divergence of up to 20 milliradians.

21  
22 In one form of the invention, an X-ray optic is  
23 interposed between the X-ray generator and the  
24 sample location, and is arranged to receive said  
25 beam and to transmit the X-rays as a substantially  
26 parallel beam.

27  
28 In an alternative and higher resolution form, no X-  
29 ray optic is used, and any unacceptable doubling of  
30 the image is removed or compensated by software.

31

1 The detector may be positioned to receive deflected  
2 X-rays transmitted through the sample.

3 Alternatively, the detector may be positioned to  
4 receive deflected X-rays reflected from the sample.

5

6 The X-ray generator is preferably adapted to produce  
7 a source spot size of 100  $\mu\text{m}$  or less and preferably  
8 has an exit window less than 20 mm from the target.

9

10 Preferably, the system resolution is about 25  $\mu\text{m}$  or  
11 better and the detector is located 5 - 10 mm from  
12 the sample location.

13

14 The X-ray optic is preferably a lobster eye optic  
15 comprising a number of X-ray reflective plates set  
16 at a slight angle from each other so that the output  
17 beam is substantially parallel. Typically, the  
18 plates are about 150  $\mu\text{m}$  thick and are coated with  
19 gold.

20

21 The detector is suitably a charge coupled device,  
22 most preferably a digital CCD.

23

24 The present invention also provides an X-ray  
25 topographic apparatus comprising an X-ray  
26 topographic system as defined above, stepping means  
27 for producing relative stepwise motion between the  
28 system and a sample to be inspected, the step size  
29 being a function of the beam area and spectral  
30 profile, and image processing means for reading out  
31 the pixel data of the detector between successive  
32 steps.

1 Other features and advantages of the present  
2 invention will be apparent from the following  
3 description and from the appended claims.

4

5 Description of Preferred Embodiments

6

7 Embodiments of the invention will now be described,  
8 by way of example only, with reference to the  
9 drawings, in which:

10

11 Fig. 1 is a schematic side view illustrating one  
12 system embodying the invention;

13 Fig. 2 illustrates the operation of the system of  
14 Fig. 1 ;

15 Fig. 3 shows one component of Fig. 1 in greater  
16 detail;

17 Fig. 4 is a schematic representation of an  
18 apparatus incorporating the system of Fig. 1;

19 Fig. 5 illustrates an alternative form of  
20 apparatus;

21 Fig. 6 illustrates a modified system without an  
22 x-ray optic;

23 Fig. 7 is an example of an image obtained by a  
24 system embodying the invention;

25 Fig. 8 is a flow chart of an algorithm used in  
26 one form of the invention;

27 Fig. 9 illustrates geometric coordinates used in  
28 combining images;

29 Fig. 10 is a flow chart of an algorithm used in  
30 combining images; and

31 Figs. 11 and 12 are examples of combined images.

1     Embodiment of Wafer Inspection System

2

3     The embodiment of Figs. 1 to 3 is particularly  
4     suitable for slip band detection in Si wafers up to  
5     300 mm diameter.

6

7     Referring to Fig. 1, a silicon wafer 10 is inspected  
8     by a topographic system comprising an X-ray  
9     generator 12, an X-ray optic element 14, and a  
10    detector indicated generally at 16.

11

12    The X-ray generator 12 is most suitably the  
13    Microsource® X-ray generator from Bede plc of  
14    Bowburn, Co. Durham, which is the subject of WO  
15    98/13853. Briefly stated, the Microsource®  
16    generator comprises an evacuated X-ray tube with  
17    external focussing coils arranged to produce a spot  
18    X-ray source on the target of 100  $\mu\text{m}$  or less, and a  
19    configuration where the X-ray exit window is within  
20    5 - 10 mm of the target. The Microsource® generator  
21    is particularly suitable for use in the present  
22    invention, since it enables an X-ray optic to be  
23    positioned close to the small target spot while at  
24    the same time delivering a narrowly diverging beam  
25    to the optic.

26

27    The X-ray optical element 16 is any suitable element  
28    which will accept slightly divergent rays from the  
29    generator 12 and provide as output an area of  
30    parallel X-rays. The preferred element, as used in  
31    this embodiment, is a "lobster eye" optic; X-ray

1 optics of this type have been described in the prior  
2 art, but only in relation to use in X-ray astronomy.

3

4 As seen in Fig. 3, the lobster eye optic 14  
5 comprises a series of flat plates 18 acting as  
6 specular reflectors and mounted to be accurately  
7 radially divergent from a point half way between the  
8 point source and the mid point of each reflector.

9 In the preferred embodiment, the X-rays are copper K  
10 radiation, the plates 18 are gold coated and are  
11 about 150  $\mu$ m thick, 6 x 30 mm in area, and with 80%  
12 average reflectivity. Using a total of fourteen  
13 plates, which is the practical maximum that can be  
14 accommodated with the above thickness, gives a  
15 theoretical gain of  $1 + 14 \times 0.8 = 12$  approximately.

16

17 Reverting to Fig. 1, the output from the lobster eye  
18 optic 14 is a substantially parallel beam 20 which  
19 is incident on the wafer 10. The undeflected beam  
20 20a is intercepted by a beam stop 22. The deflected  
21 beam 20b is incident on an electronic detector  
22 element 24 which will be described below.

23

24 More specifically, the beam 20 has a divergence of  
25 about 2 mr and is segmented into a number of  
26 stripes, about 30 mm long. Each stripe is  
27 polychromatic and gives rise to a  $K\alpha_1$ ,  $K\alpha_2$  stripe on  
28 the image (see Fig. 2). Hence the image from one  
29 stripe will be doubled.

30

31 In the usual method of Lang topography, the specimen  
32 and the photographic plate are translated together

1 through the beam. A defect is seen twice, once by  
2 the  $K\alpha_1$  beam and later, after the plate has  
3 translated, by the  $K\alpha_2$  beam. Because the distance  
4 from the specimen to the film is at least 50 mm for  
5 a large wafer, and the divergence between  $K\alpha_1$  and  
6  $K\alpha_2$  is about  $2.5 \times 10^{-3}$ , the image is doubled (by  $50$   
7  $\times 2.5 \times 10^{-3} = 0.125$  mm) and a slit, rather than just  
8 a stop, is used to select only the  $K\alpha_1$  beam.

9  
10 In the present arrangement, the image is not doubled  
11 when the wafer 10 is static; the  $K\alpha_2$  is simply of  
12 weaker intensity, and other components from  
13 Bremsstrahlung are also there without any image  
14 multiplication. This is actually a spectrally-  
15 reduced segment of a white radiation topograph.

16  
17 If now we translate the wafer 10 by a step, we will  
18 get a faithful image of the part of the specimen  
19 that is now struck by the beam. With a film  
20 detector this would of course be superimposed on the  
21 first image. However, by using an electronic  
22 detector element 24 it is possible to store the  
23 images from successive steps electronically to  
24 produce an image for the entire wafer 10.

25  
26 As long as all of the wafer 10 is scanned uniformly  
27 by all of the beam, it does not matter what is the  
28 intensity profile in the beam. The basic  
29 requirement for the optic 14 is that as much  
30 intensity as possible is reflected/scattered  
31 parallel to the original direct beam.

1 It is extremely desirable that the generator 12  
2 provides a "point" (as discussed below) source. A  
3 line source perpendicular to the plane of Fig. 2  
4 will give coma in the same direction, and a line  
5 source parallel to the plane of Fig. 2 and to the  
6 wafer will give doubled images from the  $K\alpha_1$ ,  $K\alpha_2$   
7 components.

8  
9 Turning to questions of resolution and source size,  
10 the usual equation for resolution,  $d$ , applies:

11 
$$d = hb/a$$

12 where  $a$  and  $b$  are as defined in Fig. 2, and  $h$  is the  
13 source dimension perpendicular to the Figure. In the  
14 arrangement of Fig. 1, the dimensions of the  
15 Microsource® X-ray source determine  $a$  as no smaller  
16 than 75 mm, and  $b$  could readily be 15 mm.

17  
18 X-ray topographers have customarily striven to meet  
19 a target of 1  $\mu\text{m}$  resolution, which may be desirable  
20 for academic research but involves very long (days)  
21 exposure and processing time. Since the potential  
22 exposure reduces as the square of resolution, huge  
23 gains can be made by relaxing the target resolution.  
24 For use in the inspection and quality control of  
25 semiconductor materials, it is necessary to see  
26 isolated dislocations, but not the details of their  
27 interactions. We have concluded that a resolution  
28 of 25  $\mu\text{m}$  is ample for this, and indeed up to 100  $\mu\text{m}$   
29 could be usable.

30



1 Aiming for 25  $\mu\text{m}$  resolution implies an X-ray source  
2 spot of 125  $\mu\text{m}$ . Considerations of coupling to an  
3 optic could limit the spot size to 100  $\mu\text{m}$  which in  
4 the Microsource® generator could be run at 100W, and  
5 give a resolution of 20  $\mu\text{m}$  on the detector screen.

6  
7 There is still a risk of image doubling from the  $K\alpha$   
8 doublet, since the beams will still diverge from a  
9 defect position by  $10^{-3}$  on their way to the detector.  
10 However, if the detector is within 10 mm of the  
11 wafer the blurring will only be 25  $\mu\text{m}$ , which is  
12 acceptable, and it should be possible to achieve a  
13 distance of 2-5 mm between sample and detector.

14  
15 For the above-described embodiment and benchmark  
16 measurements, we have calculated that the exposure  
17 time for examining a 8" (200 mm) Si wafer, using 100  
18 W on a Cu target, would be in the region of 5-10  
19 minutes. In contrast, a known system uses 2.5 m  
20 between source and wafer with image capture on film,  
21 15 kW source power, and 1 hour exposure time. It  
22 also requires photographic film processing.

23  
24 Considering now the detector 16, the basic  
25 requirement is a detector which gives an electric  
26 signal output of received X-ray intensity in a pixel  
27 array. The preferred detector is a digital CCD  
28 detector in a rectangular configuration, e.g. 2000  
29 by 200 pixels. Such detectors are available with a  
30 resolution from 24 down to about 7.5  $\mu\text{m}$ . The use of  
31 a detector of this aspect ratio allows the detector

1 to be placed very close to the wafer. A less  
2 sophisticated alternative is the Photonic Science  
3 Hires detector which can be configured to give  
4 30  $\mu\text{m}$  resolution over about 12 x 15 mm, or 15  $\mu\text{m}$   
5 resolution over 6 x 7.5 mm.

#### 6 7 Embodiment of Wafer Inspection Apparatus

8  
9 Turning now to Fig. 4, there is schematically  
10 depicted an apparatus, incorporating the foregoing  
11 system, for inspection of wafers. The apparatus 40  
12 includes an XY table 42 driven along orthogonal axes  
13 by servomotors (not shown) in known manner, a  
14 Microsource® controller 44, an interlock controller  
15 46, and a servomotor controller 48. The apparatus  
16 40 is of compact dimensions, typically about 650 mm  
17 wide by 750 mm high.

#### 18 19 Embodiment of Boule Inspection by Reflection

20  
21 The invention as thus far described operates in  
22 transmission. It may equally be used in a  
23 reflection mode, either with wafers or, as  
24 illustrated in Fig. 5, with a boule 50. A Si boule  
25 may typically be 300 mm diameter by about 1 m  
26 length. The entire boule or selected parts only may  
27 be inspected by providing servomotor drives to  
28 produce stepwise relative motion between the boule  
29 50 and the inspection system 10,12,14 in rotation  
30 and axially. Again, the requirement is to acquire a  
31 digital representation by stepping the detector  
32 across the area of interest.

1 It will be understood that the image data at each  
2 step is read out and used to build up an image of  
3 the entire area inspected. Typically, the value for  
4 each pixel will be stored in a corresponding memory  
5 location until the entire image can be displayed on  
6 a screen or printed. It may be necessary to use  
7 commercially available image processing software to  
8 normalise image intensities and to merge the images  
9 from the separate steps together.

10

#### 11 Embodiment of System without X-ray Optic

12

13 Turning now to Fig. 6, a modified form of the  
14 present invention will be discussed. Fig. 6 is  
15 similar to Fig. 1 and similar parts are denoted by  
16 like reference numerals. In Fig. 6, however, the X-  
17 ray optic such as lobster eye optic 14 is omitted.  
18 This has the result that the X-ray beam 20 reaching  
19 the sample 10 is more divergent than in the previous  
20 embodiments, and the radiation deflected by the  
21 sample has a broader spectral range. When an optic  
22 is used the divergence can in practice be limited to  
23 about 2 mr. When no optic is used, the divergence  
24 depends on the nature and operating conditions of  
25 the X-ray source, but typically a relatively large  
26 divergence of up to 20 mr may be used.

27

28 In one example of such an arrangement, a  
29 Microsource® generator was used with a copper anode.  
30 The x-ray imaging system was a Photonic Science  
31 imager with 512 x 512 pixels each with a nominal  
32 size of 30 x 30  $\mu\text{m}$ . This was connected to a 700 MHz

1 Pentium III based PC with 128 Mbytes of RAM, and  
2 using a PCVision frame grabber.

3  
4 Fig. 7 is a representation of one image obtained  
5 from the arrangement of Fig. 6 examining an edge  
6 region of a silicon wafer. This shows two  
7 diffraction streaks from the 115 glancing incidence  
8 Bragg reflection from a Si(001) sample. The left  
9 and right streaks are respectively  $K\alpha_1$  and  $K\alpha_2$   
10 diffraction streaks. The streaks are curved at the  
11 bottom due to the curved edge of the sample. A  
12 defect is visible about 2/3 of the way down from the  
13 top of the  $K\alpha_1$  streak as a bright white region.

14  
15 In the embodiments of Figs. 1 to 5, the  $K\alpha_1$  and  $K\alpha_2$   
16 diffraction streaks, due to the presence of the  
17 optic, are sufficiently close together to be treated  
18 as a single image for most purposes. In the present  
19 embodiment this may be possible for some less  
20 critical applications, but if not then the images  
21 produced by the detector can be manipulated by  
22 software.

23  
24 For any known specimen-detector distance there is a  
25 known divergence of the  $K\alpha_1$  and  $K\alpha_2$  beams. This in  
26 effect gives a slight magnification of the image,  
27 and can be corrected completely by demagnifying the  
28 image in one dimension only (in the incidence  
29 plane). This removes completely the effects of the  
30 spectral distribution upon the resolution, which  
31 thus becomes limited only by the detector  
32 resolution, which is expected to improve with

1 progress in the semiconductor technology, and can be  
2 sub-micron. However, this correction will not be  
3 possible where the specimen is not reasonably  
4 planar.

5  
6 As an alternative, or where there is a bent or  
7 distorted specimen, the  $K\alpha_1$  and  $K\alpha_2$  images can be  
8 separated in the software and processed to maintain  
9 resolution and intensity, as described below.

10  
11 The foregoing description has assumed a single  
12 exposure at each step of the sample. However,  
13 currently available electronic X-ray detectors are  
14 not sufficiently sensitive to allow such operation,  
15 which would result in an unacceptable signal to  
16 noise ratio. It is convenient to use a detector  
17 such as a CCD detector operating in a conventional  
18 raster scan such as 525 lines at 60 Hz or 625 lines  
19 at 50 Hz. In this case, a significant number of  
20 frames of the same sample area will have to be  
21 integrated, i.e. a cumulative sum taken for each  
22 pixel. With available technology it may be  
23 necessary to integrate between 10 and 2000 frames  
24 before stepping to the next area of the sample.

25

#### 26 Examples of Software

27

28 There now follows one example of software by which a  
29 number of frames in a wider format can be  
30 integrated.

31

1    Integrating Image

2

3    This example employs an algorithm as shown in Fig. 6  
4    and further described as follows (text in a bold  
5    font refer to variables defined in the program  
6    source code):-

7

8    1.    The routine is initialised by creating a 32-bit  
9    floating point image (**im\_expose**) and an 8-bit (byte)  
10   image (**im\_temp**). The X-ray imaging system, assumed  
11   to be connected to channel 0 of the PCVision card,  
12   is selected as the video source.

13

14   2.    Acquire (snap) a single frame from the X-ray  
15   imaging system into the byte image, **im\_temp**.

16

17   3.    If the gray scale exposure type is selected  
18   continue to step 4. If the binary threshold  
19   exposure type is selected, convert the current  
20   frame, **im\_temp**, to a two-level (binary) image.  
21   Pixel values in **im\_temp** below the specified  
22   threshold limit are set to zero (black) whereas  
23   pixel values above the threshold value are set to  
24   255 (white).

25

26   4.    Add the current frame, **im\_temp**, to the  
27   integrated image, **im\_expose**. A 32-bit floating  
28   point image is used to store the integrated image so  
29   as to avoid overflow problems. The image **im\_temp** is  
30   added to **im\_expose** on a pixel-by-pixel basis. The  
31   resultant image is multiplied by a scaling factor,  
32   which in this case is set equal to 1.0.

- 1     5. Repeat steps 2-4 until the specified number of  
2 frames, designated by the **Frames** variable, is  
3 integrated.  
4
- 5     6. Finally, convert the 32-bit floating point  
6 image **im\_expose** to an 8-bit byte image. In order to  
7 convert between 32-bit and 8-bit image formats the  
8 pixel values are scaled to map to the value range 0  
9 to 255. This scaling can be achieved in three ways:  
10 a) by dividing **im\_expose** by the number of frames  
11 integrated. b) automatically based on the minimum  
12 and maximum pixel values and c) by adding an offset  
13 and multiplying by a scale factor. In the latter  
14 case, values that are still outside the 0 to 255  
15 range are clipped. Pixel values less than 0 are set  
16 equal to 0 while those greater than 255 are set to a  
17 value of 255.  
18
- 19     7. Save the final 8-bit integrated image to a disk  
20 file with a specified name.  
21
- 22     8. Display the integrated image in the main  
23 program window.  
24

#### 25     Combined Integrated Images

26

27     The integrated images acquired according to the  
28 algorithm described in the previous section contain  
29  $K\alpha_1$  and  $K\alpha_2$  diffraction streaks respectively from  
30 positions  $(\chi_1, \gamma_1)$  and  $(\chi_2, \gamma_2)$  on the sample. The  
31 Tile command combines a distribution over an  
32 extended region.

1 In order to understand the Tile algorithm, we must  
 2 define the coordinate spaces used to describe the  
 3 location of pixels within an image and the location  
 4 and size of a rectangular region of interest (RROI)  
 5 within an image. It is also important to define the  
 6 transformation that maps a spatial coordinate  $(\chi, \gamma)$   
 7 on the sample to a pixel coordinate in an image or  
 8 RROI.

9 Referring to Fig. 7, the origin of an image has the  
 10 coordinates  $(0,0)$  and refers to the pixel at the  
 11 top, left-hand corner of the image. The horizontal  
 12 side of the image is denoted by  $X$  and the vertical  
 13 side of the image by  $Y$ . Hence, the pixel at the  
 14 bottom, right-hand corner of the master image has  
 15 the coordinates  $(X,Y)$ .

16  
 17 The origin of a RROI has the coordinates  $(x,y)$   
 18 relative to the origin of its parent image. The  
 19 horizontal extent of an RROI is denoted by  $dx$  and  
 20 the vertical extent by  $dy$ . Hence, the pixel at the  
 21 bottom, right-hand corner of an RROI has the  
 22 coordinates  $(x+dx, y+dy)$  relative to the origin of  
 23 its parent image.

24  
 25 Fig. 7 shows the relationship between the  
 26 coordinates of an image and an RROI. The equations  
 27 used to transform between world coordinates  $(x,y)$   
 28 and RROI coordinates  $(x,y)$  within an image expressed  
 29 as follows

$$30 \quad x = (x - x_0) / dx$$

$$31 \quad y = (y - y_0) / dy$$

32



1 where ( $x_0, y_0$ ) is the origin expressed in world  
 2 coordinates and  $dx$  and  $dy$  are the pixel dimensions  
 3 of the X-ray imaging camera in the x-(horizontal)  
 4 and y-(vertical) directions, respectively. Here we  
 5 have assumed that the senses of the x- and y-  
 6 directions are identical to those within the image.  
 7 The pixel coordinates for both images and RROI's are  
 8 arranged such that the x-ordinate increases from  
 9 left to right (horizontal). The y-ordinate  
 10 increases from top to bottom (vertical).

11  
 12 The algorithm employed by the Tile command is shown  
 13 in Fig. 8 and further described as follows (text in  
 14 bold font refer to variables defined in the program  
 15 source code):

- 16  
 17 1. The routine is initialised by creating a 32-bit  
 18 floating point image (**im\_tile**) and rectangular  
 19 region of interest (RROI) within this image  
 20 (**rroi\_tile**). The X-ray imaging system, assumed to  
 21 be connected to channel 0 of the PCVision card, is  
 22 selected as the video source.
- 23  
 24 2. From a user selected .ini file, read the origin  
 25 (**OriginX**, **OriginY**) and horizontal and vertical pixel  
 26 sized, denoted by **ScaleX** and **ScaleY**, respectively in  
 27 world coordinates.
- 28  
 29 3. Read the position (**x**, **y**) and horizontal and  
 30 vertical dimensions denoted **dx** and **dy**, respectively  
 31 from the .ini file. These values are in world units  
 32 (typically mm). Also read the name of the

1 integrated image file associated with this world  
2 position.  
3  
4 4. Create a temporary 8-bit image, **im\_temp**, and  
5 read the file obtained in step 3 into this image.  
6  
7 5. Create RROI within the temporary image,  
8 **rroi\_temp**. The starting position and size of  
9 **rroi\_temp** is selected to include one, or both, of  
10 the diffraction streaks.  
11  
12 6. Subtract a constant value from **im\_temp** on a  
13 pixel-by-pixel basis, the constant value being the  
14 average pixel value within a region far from either  
15 one of the diffraction streaks, i.e. the background  
16 pixel value.  
17  
18 7. Move the RROI **rroi\_tile** according to equation  
19 1.1. Adjust the size of the **rroi\_tile** to match that  
20 of **rroi\_temp**.  
21  
22 9. Add the RROI, **rroi\_temp**, to the topograph RROI,  
23 **rroi\_tile**. A 32-bit floating point image is used to  
24 store the topograph so as to avoid overflow  
25 problems. The image **rroi\_temp** is added to **rroi\_tile**  
26 on a pixel-by-pixel basis. The resultant image is  
27 multiplied by a scaling factor, which in this case  
28 is set equal to 1.0.  
29  
30 10. Delete the temporary image, **im\_temp**, and RROI,  
31 **rroi\_temp**.  
32

- 1 11. Repeat steps 3-9 until all integrated image  
2 files in the user selected .ini file have been  
3 processed.  
4
- 5 12. Convert the 32-bit floating point image **im\_tile**  
6 to an 8-bit byte image. In order to convert between  
7 32-bit and 8-bit image formats the pixel values are  
8 scaled to map to the value range 0 to 255. This  
9 scaling can be achieved in three: a) by dividing  
10 **im\_expose** by the number of frames integrated. b)  
11 automatically based on the minimum and maximum pixel  
12 values and c) by adding an offset and multiplying by  
13 a scale factor. In the latter case, values that are  
14 still outside the 0 to 255 range are clipped. Pixel  
15 values less than 0 are set equal to 0 while those  
16 greater than 255 are set to a value of 255.  
17
- 18 13. Save the final 8-bit integrated image to image  
19 to a disk file with a specified name.  
20
- 21 14. Delete the image **im\_tile** and associated RROI,  
22 **rroi\_tile**.  
23
- 24 15. Finally, display the integrated image in the  
25 main program window.  
26

#### 27 Examples of Expose and Tile

28

29 Figs. 11 and 12 show selected reflection topographs  
30 created using the Expose and Tile commands described  
31 above. All of the topographs have been inverted to  
32 facilitate comparison with conventional X-ray

1 topography. White regions are those areas that  
2 weakly diffract X-rays whereas black regions are  
3 those that diffract strongly.

4  
5 Figs. 11 and 12 show a reflection topograph produced  
6 using both the  $K\alpha_1$  and  $K\alpha_2$  diffraction streaks.  
7 Integrated images were collected at a horizontal  
8 interval of 0.1 mm with 250 frames integrated in  
9 each image (this corresponds to an acquisition time  
10 of about 12 secs per image). A pixel size of 0.28  
11 mm was used instead of the nominal value of 0.30 mm  
12 as this resulted in the sharpest topographs.

13  
14 When acquiring the integrated images used to create  
15 the topograph shown in Fig.11, the sample was  
16 accurately aligned such that the diffraction streaks  
17 were vertical. This is not the case with the  
18 integrated image shown in Fig.12. In this case, we  
19 immediately see that the diffraction streaks are  
20 inclined a few degrees away from the vertical  
21 direction. This was due to the tilt ( $\chi$ -axis) of the  
22 sample being improperly adjusted with respect to the  
23 incident X-ray beam. For flat samples it is easy to  
24 align the sample such that the diffraction streaks  
25 are vertical. However macroscopically bent or  
26 distorted sample may lead to diffraction streaks  
27 that are inclined to the vertical direction. If  
28 this is indeed the case, the final topograph will be  
29 blurred or contain ghost images due to the  $K\alpha_1$  and  
30  $K\alpha_2$  radiation not overlapping. A rather contrived  
31 example of this effect is shown in Fig.12. This

1 topograph was created using both the  $K\alpha_1$  and  $K\alpha_2$   
2 diffraction streaks with the  $\chi$ -axis adjusted so that  
3 these streaks were several degrees away from the  
4 vertical direction.

5  
6 In order to remove the blurring of a topograph from  
7 a poorly aligned or macroscopically bent sample, we  
8 could of course use only the  $K\alpha_1$  diffraction streak  
9 to create the topograph. However, in doing this we  
10 would neglect 1/3 of the available intensity i.e.  
11 the intensity contained in the  $K\alpha_2$  diffraction  
12 streak. Furthermore, this procedure would not  
13 correct the geometric distortion (slanting) of the  
14 topograph which is also apparent in Fig. 12.

15  
16 Addition of  $K\alpha$  and  $K\alpha_2$  Images

17  
18 To create a topograph using all of the available  
19 intensity without any blurring or geometric  
20 distortions we propose the following modification to  
21 the basic Tile algorithm described above.

22  
23 1. Create a topograph using the basic Tile  
24 algorithm with the RROI in each integrated image  
25 defined so as to include only the  $K\alpha_1$  diffraction  
26 streak.

27  
28 2. Repeat step 1 but define the RROI so as to  
29 include only the  $K\alpha_2$  diffraction streak.

30

1     3.     Perform affine transformations on the  
2     topographs created in steps 1 and 2 so as to map the  
3     K $\alpha$ 1 and K $\alpha$ 2 images on top of one another.

4  
5     4.     Add the transformed K $\alpha$ 1 and K $\alpha$ 2 topographs  
6     together.

7  
8     Here, an affine transformation is a generalised name  
9     for as yet unspecified translation, rotation and  
10    shear image processing operations.

11  
12    To determine and correct the angle  $\alpha$  at which the  
13    diffraction streaks are inclined to the vertical  
14    direction we propose the following simple scheme.  
15    First we define two RROI's at the top and bottom few  
16    percent of an integrated image. These RROI's are  
17    then projected onto the horizontal axis, that is the  
18    pixel values are summed along a horizontal line in  
19    the image. The x-positions of the maximum pixel  
20    values (by fitting the projection to a peak function  
21    to obtain sub-pixel accuracy) at the top and the  
22    bottom of the image could be fitted to a linear  
23    equation (straight line through the two points) to  
24    determine  $\alpha$ . This procedure would be repeated for  
25    all integrated images comprising the final  
26    topograph. The image is then sheared by another  
27    affine transformation that corrects the value of  $\alpha$   
28    to zero, before performing the stepwise integration.

29  
30

1    Modifications

2

3    Modifications may be made to the above embodiments.

4

5    It is possible to use X-ray optics other than  
6    lobster eye optics, provided a substantially  
7    parallel output is obtained. For example, parabolic  
8    specular or multilayer optics could be used,  
9    particularly parabolic graded multilayers, but these  
10   are likely to be more expensive than lobster eye  
11   optics.

12

13   The aperture on either side of the optic could be  
14   extended by using non-graded multilayer plates, or  
15   still further by using crystal reflectors such as  
16   mica.

17

18   The width of 30 mm is believed to be a practical  
19   limit to lobster eye optics at present. The  
20   Microsource® generator can provide a total aperture  
21   of 40 - 45 mm at a distance of 50 mm, and so if a  
22   wider optic could be made the exposure could be  
23   decreased in proportion.

24

25   The use of a less sophisticated optic than that  
26   described would also give a useful, though somewhat  
27   poorer, performance. Even a lobster eye optic of  
28   only two plates would give a gain of 2.6x and a  
29   processing time for a 8" wafer of 20 - 25 mins.

30

31   The use of the Microsource® X-ray generator is  
32   preferred for two reasons. One is the ability to

1 place the optic very close to the X-ray source. The  
2 other is that the power and source size can be  
3 controlled electronically to alter the tradeoff  
4 between resolution and throughput according to the  
5 needs of the measurement, with no mechanical  
6 alterations. The latter factor also makes it  
7 possible to scan the sample at relatively low  
8 resolution to detect areas with some discrepancy,  
9 and then to inspect such areas in greater detail.

10

11 However, the invention is not limited to the use of  
12 the Microsource® generator, and other means of  
13 producing X-rays may be used.

14

15 Although described with reference to the detection  
16 of slip bands in Si, the invention is useful with  
17 other materials, such as defect detection in EUV  
18 optical material such as  $\text{CaF}_2$  and in SiC and III-V  
19 crystals.

20

21 Other modifications and improvements may be made  
22 within the scope of the invention.